

**REPORT DOCUMENTATION PAGE**Form Approved  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

<b>1. REPORT DATE (DD-MM-YYYY)</b> 01 - 09 - 2005		<b>2. REPORT TYPE</b> Final Report		<b>3. DATES COVERED (From - To)</b> 01/04/2001 - 31/10/2004	
<b>4. TITLE AND SUBTITLE</b> On-line Planning and Mapping for Chemical Plume Tracing				<b>5a. CONTRACT NUMBER</b>	
				<b>5b. GRANT NUMBER</b> N00014-01-1-0906	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b> Jay A. Farrell				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>  Department of Electrical Engineering University of California, Riverside Riverside, CA 92506				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>  Office of Naval Research 800 N. Quincy St. Arlington, VA 22217 - 5000				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> ONR	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION / AVAILABILITY STATEMENT</b>  Distribution Unlimited <div style="text-align: center;"><b>DISTRIBUTION STATEMENT A</b> Approved for Public Release Distribution Unlimited</div>					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> The objective of this project was to research, develop, and implement on-vehicle planning and mapping theory and software to find, trace, and map chemical plumes. This objective included accurate declaration of chemical source locations. Our planning methodologies demonstrated successful chemical plume tracing in four separate sets of in-water tests in two distinct locations with a variety of environmental conditions. The final test in June 2003 test at Duck NC demonstrated chemical plume tracing over a distance of 975 m between first detection and declared source location. Average source declaration accuracy was on the order of 13m. The plume and source likelihood mapping theory and methods developed under this project have utility in chemical transport applications in both oceanic and atmospheric environments. Chemical plume tracing capabilities, such as those demonstrated for the first time on this project, have utility in searching for environmentally interesting phenomena, unexploded ordnance, undersea wreckage, and sources of hazardous chemicals or pollutants.					
<b>15. SUBJECT TERMS</b> Chemical plume tracing, Autonomous vehicles, reactive behavior based planning					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>  Unlimited	<b>18. NUMBER OF PAGES</b>  4	<b>19a. NAME OF RESPONSIBLE PERSON</b> Jay A. Farrell
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			<b>19b. TELEPHONE NUMBER</b> 951-827-2159

Final Report

**DISTRIBUTION STATEMENT A**

Approved for Public Release  
Distribution Unlimited

GRANT # N00014-01-1-0906

PRINCIPAL Investigator: Jay A. Farrell

INSTITUTION: University of California, Riverside

GRANT TITLE: On-line Planning and Mapping for Chemical Plume Tracing

AWARD PERIOD: April 1, 2001 - June 30, 2004  
with a no cost extension through 10/31/2004

OBJECTIVE: The objective of this project was to research, develop, and implement on-vehicle planning and mapping theory and software to support the ONR Chemical Sensing in the Marine Environment (CSME) Program in its objective to find, trace, and map chemical plumes. This objective included accurate declaration of chemical source locations. The scope of this effort included development of the theory, implementation of the algorithms in software, evaluation and optimization of these algorithms in simulation, and demonstration of these algorithms onboard a Navy autonomous underwater vehicle.

APPROACH: We developed the theory and algorithms to perform on-line mission planning, reaction, and plume mapping to enable an AUV to track an odor plume to its source and to accurately declare the source location. In off-line analysis, planning and mapping are used jointly to enable long-term optimization of the vehicle maneuvers to reach the mission goal within the mission constraints. Such off-line methods built on Hidden Markov models, the Viterbi algorithm, and Bayesian reasoning. This analysis resulted in algorithms to estimate a source likelihood map [10] and a plume likelihood map [6]. Based on those maps, we developed algorithms to construct the trajectory most likely to detect chemical [6]. The on-vehicle planner was built using reactive behavior-based methods. Specific reactive behaviors were designed and optimized for finding the plume, tracing the plume, reacquiring contact with a lost plume, and declaring a source location. Additionally, reaction was used to instantiate vehicle safety behaviors (e.g., staying in the operational area). The resulting algorithms have been demonstrated in-water on a SPAWAR REMUS. Details of the approach developed in this research project are described in [1-10]. The final planner and its on-vehicle plume tracing results are documented in [8].

ACCOMPLISHMENTS: Our planning methodologies demonstrated successful chemical plume tracing in four separate sets of tests in two distinct locations with a variety of environmental conditions. The August 2002 test in San Diego Bay

20050909 045

was the first demonstration of Adaptive Mission Planning (AMP) on a REMUS vehicle. The September 2002 tests at San Clemente Island offered an opportunity for preliminary on-vehicle testing of the chemical plume tracing software. The November 2002 test at San Clemente Island was the first successful demonstration of chemical plume tracing with source declaration. The April 2003 test at San Clement Island was the first successful demonstration of chemical plume tracing with post-declaration maneuvers designed to image the source using sidescan sonar. The June 2003 test at Duck NC was the first demonstration of multiple plume tracing and multiple source declaration. That test also demonstrated chemical plume tracing over a distance of 975 m between first detection and declared source location. Average source declaration accuracy was on the order of 13m. Details of the November 2002, April 2003, and June 2003 operations can be found in [3,4,5,7,8].

CONCLUSIONS: This project has contributed to the theory and practice of on-line mission planning, reactive planning, and chemical plume tracing. The theoretical contributions are documented in articles [1,2,6,8,9,10]. The experimental demonstrations of the working technology are documented in [3,4,5,7,8,9]. Advanced vehicle control combined with reactive mission planning offer significant potential for advancing the level of autonomy achievable for underwater vehicles on missions of interest to the Navy such as ship hull inspection, swimmer defense, and unexploded ordnance disposal.

SIGNIFICANCE:

1. This project demonstrated reactive behavior-based planning on an important extended-duration mission over a large region and in a real environment. This is a significant transition from laboratory to practice.
2. Chemical plume tracing capabilities, such as those demonstrated for the first time on this project, have utility in searching for environmentally interesting phenomena, unexploded ordnance, undersea wreckage, and sources of hazardous chemicals or pollutants.
3. The plume and source likelihood mapping methods developed under this project have utility in chemical transport applications in both oceanic and atmospheric environments.

PATENT INFORMATION: None filed

AWARD INFORMATION: None

PUBLICATIONS:

1. Wei Li, Jay A. Farrell, and Ring T. Cardé, Tracking of Fluid-Advection Odor Plumes: Strategies Inspired by In-

sect Orientation to Pheromone, Adaptive Behavior, 9:3/4, pp. 143-170, 2001.

2. Jay A. Farrell, John Murlis, Wei Li, Ring T. Cardé, Filament-Based Atmospheric Dispersion Model to Achieve Short Time-Scale Structure of Odor Plumes, Environmental Fluid Mechanics, Vol. 2, pp. 143-169, 2002.
3. R. M. Arrieta, J. A. Farrell, W. Li, S. Pang, "Initial Development and Testing of an Adaptive Mission Planner for a Small Unmanned Underwater Vehicle," Proc. Of the 22nd Int. Conf. On Offshore Mechanics and Arctic Engineering, OMEA2003-37273, AMSE, 2003.
4. J. A. Farrell, W. Li, S. Pang, R. M. Arrieta, Chemical Plume Tracing Experimental Results with a REMUS AUV, MTS/IEEE Oceans 2003, pp. 962-968, 2003.
5. S. Pang, J. A. Farrell, R. M. Arrieta, and , W. Li, AUV Reactive Planning: Deepest Point, MTS/IEEE Oceans 2003, pp. 2222-2226, 2003.
6. J. A. Farrell, S. Pang, W. Li, Plume Mapping via Hidden Markov Methods, IEEE Trans. SMC-B, Vol. 33:6, pp. 850-863, 2003.
7. J. A. Farrell, S. Pang, W. Li., and R. M. Arrieta "Biologically Inspired Chemical Plume Tracing Demonstrated on an Autonomous Underwater Vehicle", IEEE Systems, Man, and Cybernetics Conference, Hague, Netherlands, pp. 5991-5996, September 2004.
8. J. A. Farrell, S. Pang, and W. Li, "Chemical Plume Tracing via an Autonomous Underwater Vehicle" IEEE J. of Oceanic Engineering, Vol. 30:1, January 2005.
9. W. Li, J. A. Farrell, S Pang, R. M. Arrieta, Moth Behavior Based Subsumption Architecture for Chemical Plume Tracing on A REMUS Autonomous Underwater Vehicle, submitted to IEEE Transaction on Robotics and Automation.
10. S. Pang and J. A. Farrell, "Chemical Plume Source Localization," submitted to IEEE Transactions on Systems, Man, and Cybernetics, Part B.